PHOTOGRAMMETRIC ACCURACY OF REAL TIME KINEMATIC ENABLED UNMANNED AERIAL VEHICLE SYSTEMS

Study conducted by the University of Colorado, Denver and Juniper Unmanned Aerial Systems for the United States Geological Survey

10/19/2015

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ABSTRACT

Unmanned Aerial Vehicles (UAV), also known as Unmanned Aerial Systems (UAS), are becoming a preferred tool for geospatial data collection. With the large number of UAVs coming into the market, it is important for the end user to know which platforms have the capabilities to collect accurate data in accordance with the user's requirements and needs. The importance of this information is critical for most projects as the UAVs fly at lower altitudes and can offer higher image resolutions and more accurate data collection than traditional aircraft.

The purpose of this study is to research and compare different approaches for image data collection with RTK enabled UAV platforms. In order to conduct this research, three missions of imagery data collection of the same area were completed. The first two missions collected images with a GPS RTK unit on the UAV. The third mission collected data without this GPS RTK unit.

Prior to the flight, a ground control network of about 31 points was established, and these points were surveyed with GPS. One third of the control points were surveyed as RTK GPS and the rest were surveyed by a static method and were post processed. Two control points were used as Base Stations.

Imagery accuracy was determined by matching it to the positions of the ground control points after processing.

INTRODUCTION

Most of the current maps and GIS databases were or are produced with the help of spatially accurate remote sensing data. A big part of this remote sensing data is composed of images collected by satellites and airplanes. While images are used as a major source for developing spatially enabled applications or used in research and everyday work, at the same time they are not providing the most accurate spatial data. It is due to the fact that images, especially collected by aerial photography, are subjects of data processing known as photogrammetry, and their accuracy depends on several factors that include, but are not limited to, camera type, camera calibration, the flight altitude, and use of ground control points. The importance of using spatially accurate models is obvious because they allow for applications that are used by numerous government agencies and private organizations. While aerial photogrammetry is a great source of spatially enabled data, it has its limitations in relation to providing very accurate or detailed information.

With UAV platforms, most of these limitations do not exist because they allow low flights and in patterns that are not possible for aircrafts or satellites. Due to this flexibility, low price, high accuracy, and faster project turn around, UAV platforms offer a unique opportunity to collect spatially accurate data that can be used in new applications in a variety of areas, like agriculture, public safety, emergency response, mining, and oil and gas industries. Most of these applications have been overlooked due to the high cost of acquiring data in conventional ways. A UAV's ability to collect and deliver spatially accurate data with a faster turn-around and at a lower cost brings new attention to these applications.

In spite of the proliferation of UAV platforms in the marketplace, many of these systems only incorporate low-grade GNSS technology to allow for geospatial analysis of the imagery or remotely sensed data. Furthermore, while many UAV operators may be well-versed in aviation operations, standards, and practices, they usually do not understand the process of precise photogrammetric methods, which include establishing controls and accurate image alignment.

Most UAV models are directed to hobbyists, using simple remote control systems and image collection sensors like GoPro.

However, a few UAV manufacturers offer more sophisticated platforms that come with flight and mission planning software. They allow the operator to prepare controlled flight plans to cover specific areas of interest. They also provide a choice of sensors, including RGB imagery, LiDAR, infrared, and multispectral. The ability to plan and execute highly accurate missions helps in delivering the most value for the investment in time, equipment, and personnel. Traditional imagery collection methods have required single-engine aircraft, helicopters, and other more costly methods. Due to the higher cost per area of collection with these methods it has been necessary to either pay a higher price or collect less frequently. UAVs offer the ability to fly through smaller areas more frequently and with greater accuracy at a much lower cost.

SUMMARY OF CONTRIBUTIONS

The location of this project is the Peaceful Valley Scout Ranch, owned by the Denver Area Council of the Boy Scouts of America. The project area was flown with their express permission and appropriate policies for safety and risk management were followed.

The surveying equipment, training, and data processing were provided by Frontier Precision, located in Arvada, Colorado. Equipment included two R-10 antennas, TSC Ranger data collector, Intuicom RTK Bridge, and a subscription to the Trimble VRS (Virtual Reference Station) with bases located in Elizabeth and Colorado Springs, Colorado. Ground control points were established and surveyed by Clay Cozart, Peter Morin, and Brian M. Coleman.

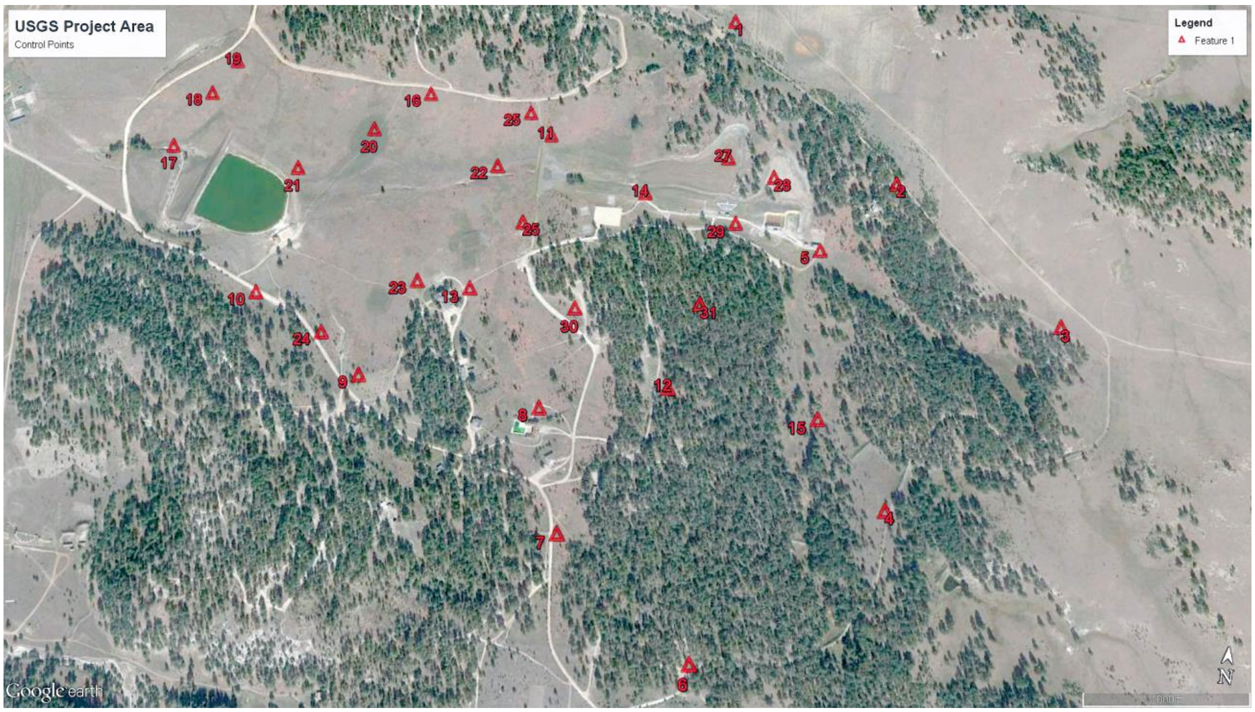
The MaVinci Sirius Pro UAV and its various components were provided by Topcon. The UAS included the aircraft, MaVinci Pro Desktop, RTK antenna, and MaVinci connector for avionics. The camera used was a Panasonic Lumix Model DMC-GX1 with a 24 megapixel resolution, a calibrated aperture, and a nominal focal length of 14mm. Flight crews included Darren Robey, Tyler Sautter, David White, Jeff Cozart, Noah Coleman, Clay Cozart, Tim Roorda, Brian Coleman, Peter Morin, and Darrel Delarosa. Flights were conducted on April 9th and May 15th, 2015.

Data processing, analyses, and the final report were completed by Apostol Panayotov, PhD, Assistant Research Professor at University of Colorado Denver, Civil Engineering Department.

GROUND CONTROL

For the purpose of this project, three study areas of interest (AOI) of about 1 sq.km each were laid out. The AOI overlap each other by almost 90%. To accomplish this study, 31 ground controls points were established across the area of interest. The RTK ground control points were collected with a Trimble R-10 and a Ranger TSC data collector. A virtual reference station provided a base for correction using the Intuicom RTK Bridge. The static ground control points were collected using a Trimble 5800 GPS.

Figure 1 - Project area map with control points



In order to make ground control easily distinguishable in images every point was marked with a white 1.5 foot wide bucket lid. Static collected points were also marked with three black lines drawn on the lid from its center to the outer side of the lid.

Figure 2 - Control point marks

The test area included open land, wooded areas, a small lake, and a typical camp infrastructure. The ground control was measured using Trimble surveying equipment that employed both static (post processed) and RTK (real time kinematic) collection techniques. The Base Stations were established at control points 13 and 19. Control points 9, 10, 13, 20, 21, 22, 23, 24, 26 were collected using 15 min fast static observation. All static points were post processed using the NOAA OPUS system. Post processing report is attached as separate document named *PVSR 05152015Baseline Processing Report.docx*.

The coordinates for the rest of the control points, including control points 1, 8, 11, 12, 14, 15, 16, 17, 18, 25, 27, 28, 29, and 30, were determined by RTK observations using an Intuicom Bridge to incorporate base stations at Elizabeth and Colorado Springs known as Virtual Reference Stations (VRS) for real time correction of the observations.

After the control network was established, Juniper Unmanned provided four files with control point data.

Baseline processing is presented in the *PVSR 05152015Baseline Processing Report.docx* file, which is attached to this report. This file provides Geodetic coordinates, Heights, and Elevations for all Static points. The Ellipsoid Height (h) came from GPS measurement. Orthometric Height (H), also known as Elevation, was calculated during GPS data processing. This information was used to compute the Geoid Height (N) for static control points (N=h-H).

Figure 3 - Table1 Control points heights

PN	Ellipsoid Height(ft)	Geoid Height (ft)	Orthometric Height(ft)
9	6886.462	-57.888	6944.350
10	6849.507	-57.870	6907.377
13	6899.740	-57.895	6957.635
19	6857.001	-57.842	6914.843
20	6860.093	-57.865	6917.958
21	6840.329	-57.863	6898.192
22	6859.042	-57.887	6916.929
23	6886.924	-57.887	6944.811
24	6868.186	-57.879	6926.065
26	6883.859	-57.897	6941.756

The file *BC-PSVR_RTK.csv* provides a list of coordinates in SPCS Colorado Central, FIPS 0502, US Survey feet for RTK control points and Orthometric Heights in US Survey feet. This file was provided by Juniper Unmanned and it is a result of GPS data processing by TBC.

Figure 4 - Table 2 RTK control points SPCS coordinates and Orthometric heights

PN	EASTING	NORTHING	Orthometric Height (ft)
PT11R	1492774.598	3277798.837	6935.03
PT14R	1492419.027	3278505.922	6948.619
PT16R	1492987.166	3276905.497	6943.221
PT17R	1492409.384	3275142.403	6868.219
PT18R	1492829.746	3275341.444	6900.783
PT25R	1492924.687	3277633.311	6947.045
PT27R	1492730.909	3279052.446	6962.122
PT28R	1492623.079	3279380.002	6966.133
PT29R	1492265.406	3279148.278	6948.281
PT30R	1491525.866	3278134.628	6979.226
PT31R	1491645.892	3278962.731	6994.03

The file *Scout Ranch NEZ Point List.pdf* provides a list of control points 1 to 15. Coordinates are in SPCS Colorado Central FIPS 0502, meter. Elevations also in meter. This file was received from Juniper Unmanned and it is a result of GPS data processing by TBC.

Figure 5- Scout Ranch NEZ point list file

Point List

ID	Northing (Meter)	Easting (Meter)	Elevation (Meter)	Feature Code
1	455294.396	999440.452	2150.860	CP
2	454955.400	999809.011	2152.950	CP
3	454684.713	1000152.259	2156.731	CP
4	454280.323	999827.059	2143.572	CP
5	454802.446	999666.204	2123.156	CP
6	453953.592	999480.493	2159.710	CP
7	454161.885	999204.277	2145.376	CP
8	454403.081	999134.256	2133.005	CP
9	454430.044	998761.475	2116.466	CP
10	454580.008	998515.145	2105.199	CP
11	454998.599	999075.087	2113.662	CP
12	454474.097	999384.724	2127.721	CP
13	454637.091	998955.955	2120.647	CP
14	454890.242	999290.590	2117.796	CP
15	454445.944	999685.754	2134.041	CP

9/26/2014 4:01:31 PM	C:\Users\Owner\Documents\Trimble Business Center\scout1.vce	Trimble Business Center

The file *Scout Ranch LLH Point List.pdf* provides a list of control points 1 to 15 with their geodetic coordinates and Ellipsoidal Height in meters. This file was received from Juniper Unmanned and it is a result of GPS data processing by TBC. In accordance with the file header the geographic coordinate system is NAD83 (2011).

Figure 6 - Scout Ranch LLH point list

Project file data		Coordinate System	
Name:	C:\Users\Owner\Documents\Trimble Business Center\scout1.vce	Name:	US State Plane 1983
Size:	584 KB	Datum:	NAD 1983 (Conus)
Modified:	2/26/2014 12:44:16 PM (UTC:-7)	Zone:	Colorado Central 0502
Time zone:	Mountain Standard Time	Geoid:	GEOID12A (Conus)
Reference number:		Vertical datum:	
Description:			

Additional Coordinate System Details

Local Site Settings			
Project latitude:	?	Ground scale factor:	1
Project longitude:	?	False northing offset:	0.000
Project height:	1981.204	False easting offset:	0.000

Point List

ID	Latitude (Global)	Longitude (Global)	Height (Global) (Meter)	Feature Code
1	N39°11'05.61113"	W104°30'56.45194"	2133.208	CP
2	N39°10'54.48875"	W104°30'41.24906"	2135.286	CP
3	N39°10'45.58981"	W104°30'27.07094"	2139.056	CP
4	N39°10'32.59162"	W104°30'40.80320"	2125.901	CP
5	N39°10'49.57925"	W104°30'47.26831"	2105.494	CP
6	N39°10'22.11874"	W104°30'55.38909"	2142.044	CP
7	N39°10'28.96999"	W104°31'06.80236"	2127.719	CP
8	N39°10'36.81579"	W104°31'09.61099"	2115.352	CP
9	N39°10'37.82035"	W104°31'25.12970"	2098.822	CP
10	N39°10'42.76898"	W104°31'35.32538"	2087.560	CP
11	N39°10'56.14742"	W104°31'11.80843"	2096.016	CP
12	N39°10'39.03085"	W104°30'59.14399"	2110.063	CP
13	N39°10'44.46641"	W104°31'16.93433"	2103.001	CP
14	N39°10'52.55822"	W104°31'02.87831"	2100.144	CP
15	N39°10'38.01205"	W104°30'46.61515"	2116.375	CP

Because there wasn't a single file that represents all points in one coordinate system, the information provide by Juniper Unmanned was used to generate the comprehensive list of control points coordinates in NAD83 (2011) geographic coordinate system. Control points which were collected by Static method are shown in red color, control points which were collected by RTK method are in black color, and points in green color are calculated from their SCPC values.

Figure 7- Table3 Control points geodetic coordinates in NAD83 (2011)

Station	Method	Latitude DMS	Longitude DMS	Latitude DD	Longitude DD	C
1	RTK	39^0 11' 05.61113" N	104^0 30' 56.45194" W	39.18489198055560	-104.51568109444400	
2	RTK	39^{0}10' 54.48875 N	104^0 30' 41.24906" W	39.18180243055560	-104.51145807222200	
3	RTK	39^0 10' 45.58981 N	104^0 30' 27.07094" W	39.17933050277780	-104.50751970555600	
4	RTK	39^0 10' 32.59162 N	104^0 30' 40.80320" W	39.17571989444440	-104.51133422222200	
5	RTK	39^0 10' 49.57925 N	104^0 30' 47.26831" W	39.18043868055550	-104.51313008611100	
6	RTK	39^0 10' 22.11874 N	104^0 30' 55.38909" W	39.17281076111110	-104.51538585833300	
7	RTK	39^0 10' 28.96999 N	104^0 31' 06.80236" W	39.17471388611110	-104.51855621111100	
8	RTK	39^0 10' 36.81579" N	104^0 31' 09.61099" W	39.17689327500000	-104.51933638611100	
9	Static	39^0 10' 37.82001" N	104^0 31' 25.13035" W	39.17717222500000	-104.52364731944400	
10	Static	39^0 10' 42.76874" N	104^0 31' 35.32568" W	39.17854687222220	-104.52647935555600	
11	RTK	39^0 10' 56.14769" N	104^0 31' 11.80857" W	39.18226324722220	-104.51994682500000	
12	RTK	39^0 10' 39.03085" N	104^0 30' 59.14399" W	39.17750856944440	-104.51642888611100	
13	Static	39^0 10' 44.46583" N	104^0 31' 16.93461" W	39.17901828611110	-104.52137072500000	
14	RTK	39^0 10' 52.55781" N	104^0 31' 02.87776" W	39.18126605833330	-104.51746604444400	
15	RTK	39^0 10' 38.01205" N	104^0 30' 46.61515" W	39.17722556944450	-104.51294865277800	
16	RTK	39^0 10' 58.34378" N	104^0 31' 23.12455" W	39.18287327222220	-104.52309015277800	
17	RTK	39^0 10' 52.81990" N	104^0 31' 45.59366" W	39.18133886111110	-104.52933157222200	
18	RTK	39^0 10' 56.95364" N	104^0 31' 43.00887" W	39.18248712222220	-104.52861357500000	
19	Static	39^0 10' 59.54479" N	104^0 31' 41.31395" W	39.18320688611110	-104.52814276388900	
20	Static	39^0 10' 55.34985" N	104^0 31' 27.70511" W	39.18204162500000	-104.52436253055600	
21	Static	39^0 10' 51.95830" N	104^0 31' 33.88021" W	39.18109952777780	-104.52607783611100	
22	Static	39^0 10' 53.53722" N	104^0 31' 16.21590" W	39.18153811666670	-104.52117108333300	
23	Static	39^0 10' 44.62620" N	104^0 31' 21.53805" W	39.17906283333330	-104.52264945833300	
24	Static	39^0 10' 40.47464" N	104^0 31' 29.01254" W	39.17790962222220	-104.52472570555600	
25	RTK	39^0 10' 57.64879" N	104^0 31' 13.89012" W	39.18268021944440	-104.52052503333300	
26	Static	39^0 10' 49.54983" N	104^0 31' 13.24475" W	39.18043050833330	-104.52034576388900	
27	RTK	39^0 10' 55.58191" N	104^0 30' 55.89433" W	39.18210608611110	-104.51552620277800	
28	RTK	39^0 10' 54.48103" N	104^0 30' 51.74939" W	39.18180028611110	-104.51437483055600	
29	RTK	39^0 10' 50.97071" N	104^0 30' 54.74140" W	39.18082519722220	-104.51520594444400	
30	RTK	39^0 10' 43.76967" N	104^0 31' 07.71546" W	39.17882490833330	-104.51880985000000	
31	RTK	39^0 10' 44.86744" N	104^0 30' 57.18294" W	39.17912984444440	-104.51588415000000	

IMAGE DATA COLLECTION

After the areas of interest were established, the UAV crew was deployed with the purpose of flying the study area and collect imagery. The chosen system was the MaVinci Sirius Pro, which included MaVinci Desktop software and an RTK base antenna. The other components were mission planning software, built-in GNSS with RTK capabilities, a GPS triggered camera, and IMU. The platform also had the ability to log and download the “a priori data or photo log” to the UAV software in order to apply corrections to the imagery.

The flights over the area of interest were conducted over several days. Collected imagery was processed in one of two ways: raw imagery without photo log matching and imagery matched with the photo log. All flights were done using standard mission planning and included setting up the UAV's Base Station directly over control point 13.

Three flights were completed resulting in three different sets of images. The imagery collected from each flight was saved and processed. The raw imagery and the "photo log" were saved as two separate files. The raw imagery is actually "unprocessed" or "unmatched" imagery. The same imagery and photo log were "processed" or "matched" in the field. This was done for Flight1 and Flight2 as each flight was intended to be used with a different number of control points collected by different surveying methods.

Flight 1 and Flight 2 were conducted with the UAV's GPS enabled and the images were post processed with the MaVinci software so that they included the GPS data in their EXIF header. Flight 3 imagery was collected with UAV's GPS unit disabled. Therefore, this set of data was used as "raw imagery" without GPS data in their EXIF header and a subset of this data was processed in old photogrammetric fashion. Because these images do not have any coordinates in their EXIF header, automatic image matching is not possible. A subset of about 64 images was selected in the center of the project area where few control points are clustered together. Then tie points were manually selected in each image and were used to stich images together in one block. Control points were also marked in each image and were used to run block adjustment.

CONTROL POINTS DATA PROCESSING

The first step in data processing was to develop a complete list of control points with their geodetic coordinates in DMS and DD, State Plane coordinates (ft.), Orthometric Height (H), Ellipsoidal Height (h) and Geoid Height (N) in meters and US Survey ft. The table *Survey Control.xlsx* provides this information as separate file.

It is important to mention that the geographic coordinates in the image EXIF header are in WGS84, while the control points were in NAD83(2011). Due to this discrepancy and the fact that the images cannot be converted from WGS84 to NAD83 (2011) in Photo Scan because the software does not have NAD83 (2011) in the library, the control point coordinates were converted to WGS84 so the image data and control points are in the same coordinate system. The coordinate conversion was done by NGS HTDP software which uses IRTF2008 as a common frame for this conversion process. This information is presented in "*NAD83 (2011) toWGS84"* tab in *Survey Control.xlsx.* The table with both NAD83 (2011), GWS 84 and their differences in Latitude, Longitude and Ellipsoidal height (h) is saved as *"WGS84-NAD83 (2011) DIFFERENCE"* tab in Survey *Control.xlsx* file and shown in Table 4.

Figure 8-Table 4 – WGS84, NAD83 (2011) coordinates, Height and their differences

	WGS84		WGS84		NAD83(2011)		WGS84 - NAD83(2011)		NAD83(2011)	WGS84	WGS84-NAD83(2011)
PN	LAT DMS	LONG DMS	LAT DD	LONG DD	LAT DD	LONG DD	LAT DIFF	LONG DIFF	ELLIP.HT (M)	ELLIP.HT (M)	ELLIP.HT DIFF(M)
1	39.1105630330	-104.3056499920	39.1848973139	-104.5156944222	39.1848919806	-104.5156810944	-0.0000053333	0.0000000056	2133.208	2132.314	-0.8940000000
2	39.1054507950	-104.3041297030	39.1818077639	-104.5114713972	39.1818024306	-104.5114580722	-0.0000053333	-0.0000000333	2135.286	2134.392	-0.8940000000
3	39.1045609010	-104.3027118910	39.1793358361	-104.5075330306	39.1793305028	-104.5075197056	-0.0000053333	-0.0000000333	2139.056	2138.162	-0.8940000000
4	39.1032610810	-104.3040851170	39.1757252250	-104.5113475472	39.1757198944	-104.5113342222	-0.0000053306	0.0000000083	2125.901	2125.007	-0.8940000000
5	39.1049598440	-104.3047316280	39.1804440111	-104.5131434111	39.1804386806	-104.5131300861	-0.0000053306	-0.0000000583	2105.494	2104.600	-0.8940000000
6	39.1022137930	-104.3055437060	39.1728160917	-104.5153991833	39.1728107611	-104.5153858583	-0.0000053306	-0.0000000056	2142.044	2141.150	-0.8940000000
7	39.1028989180	-104.3106850330	39.1747192167	-104.5185695361	39.1747138861	-104.5185562111	-0.0000053306	0.0000000639	2127.719	2126.825	-0.8940000000
8	39.1036834980	-104.3109658970	39.1768986056	-104.5193497139	39.1768932750	-104.5193363861	-0.0000053306	-0.0000000417	2115.352	2114.458	-0.8940000000
9	39.1037839200	-104.3125178330	39.1771775556	-104.5236606472	39.1771722250	-104.5236473194	-0.0000053306	-0.0000000528	2098.998	2098.104	-0.8937494772
10	39.1042787930	-104.3135373660	39.1785522028	-104.5264926833	39.1785468722	-104.5264793556	-0.0000053306	-0.0000000083	2087.734	2086.840	-0.8938433042
11	39.1056166880	-104.3111856550	39.1822685778	-104.5199601528	39.1822632472	-104.5199468250	-0.0000053306	0.0000000000	2096.016	2095.122	-0.8940000000
12	39.1039050040	-104.3059191970	39.1775139000	-104.5164422139	39.1775085694	-104.5164288861	-0.0000053306	0.0000000139	2110.063	2109.169	-0.8940000000
13	39.1044485020	-104.3116982590	39.1790236167	-104.5213840528	39.1790182861	-104.5213707250	-0.0000053306	0.0000000083	2103.045	2102.151	-0.8938918440
14	39.1052577000	-104.3102925740	39.1812713889	-104.5174793722	39.1812660583	-104.5174660444	-0.0000053306	-0.0000000194	2100.144	2099.250	-0.8940000000
15	39.1038031240	-104.3046663120	39.1772309000	-104.5129619778	39.1772255694	-104.5129486528	-0.0000053306	-0.0000000139	2116.375	2115.481	-0.8940000000
16	39.1058362970	-104.3123172530	39.1828786028	-104.5231034806	39.1828732722	-104.5230901528	-0.0000053306	0.0000000417	2098.657	2097.763	-0.8938909662
17	39.1052839090	-104.3145641650	39.1813441917	-104.5293449028	39.1813388611	-104.5293315722	-0.0000053306	-0.0000000194	2075.796	2074.902	-0.8942363650
18	39.1056972830	-104.3143056860	39.1824924528	-104.5286269056	39.1824871222	-104.5286135750	-0.0000053306	0.0000000167	2085.722	2084.828	-0.8937631034
19	39.1059563980	-104.3141361940	39.1832122167	-104.5281560944	39.1832068861	-104.5281427639	-0.0000053306	-0.0000000250	2090.018	2089.124	-0.8940190006
20	39.1055369040	-104.3127753100	39.1820469556	-104.5243758611	39.1820416250	-104.5243625306	-0.0000053306	0.0000000028	2090.960	2090.066	-0.8944624558
21	39.1051977490	-104.3133928200	39.1811048583	-104.5260911667	39.1810995278	-104.5260778361	-0.0000053306	-0.0000000389	2084.936	2084.042	-0.8943833974
22	39.1053556410	-104.3116263880	39.1815434472	-104.5211844111	39.1815381167	-104.5211710833	-0.0000053306	-0.0000000528	2090.640	2089.746	-0.8941170252
23	39.1044645390	-104.3121586030	39.1790681639	-104.5226627861	39.1790628333	-104.5226494583	-0.0000053306	-0.0000000472	2099.139	2098.245	-0.8935673544
24	39.1040493830	-104.3129060520	39.1779149528	-104.5247390333	39.1779096222	-104.5247257056	-0.0000053306	0.0000000500	2093.427	2092.533	-0.8942137116
25	39.1057667980	-104.3113938100	39.1826855500	-104.5205383611	39.1826802194	-104.5205250333	-0.0000053306	0.0000000306	2099.822	2098.928	-0.8944484606
26	39.1049569020	-104.3113292730	39.1804358389	-104.5203590917	39.1804305083	-104.5203457639	-0.0000053306	0.0000000361	2098.204	2097.310	-0.8943535154
27	39.1055601100	-104.3055942310	39.1821114167	-104.5155395306	39.1821060861	-104.5155262028	-0.0000053306	0.0000000278	2104.418	2103.524	-0.8939271068
28	39.1054500220	-104.3051797370	39.1818056167	-104.5143881583	39.1818002861	-104.5143748306	-0.0000053306	-0.0000000250	2105.640	2104.746	-0.8944823134
29	39.1050989900	-104.3054789380	39.1808305278	-104.5152192722	39.1808251972	-104.5152059444	-0.0000053306	-0.0000000056	2100.199	2099.305	-0.8941820022
30	39.1043788860	-104.3107763440	39.1788302389	-104.5188231778	39.1788249083	-104.5188098500	-0.0000053306	-0.0000000111	2109.631	2108.737	-0.8942365692
31	39.1044886630	-104.3057230920	39.1791351750	-104.5158974778	39.1791298444	-104.5158841500	-0.0000053306	0.0000000111	2114.144	2113.250	-0.8935046516
					AVERAGE DIFFERENCE		**-0.0000053308**	**-0.0000000056**			**-0.8940410524**

Then final list of control points with their geodetic coordinates in WGS84 and their Ellipsoidal (h) and Orthometric Heights (H) in meters was created. Control points collected by Static observation are presented in red and RTK collected points are in black.

Figure 9-Table 5 - Final list of control points in WGS84 (DD)

		WGS84		WGS84
PN	Method	LAT DMS	LONG DMS	ELLIP.HT (M)
1	RTK	39.1848973139	-104.5156944222	2132.314
2	RTK	39.1818077639	-104.5114713972	2134.392
3	RTK	39.1793358361	-104.5075330306	2138.162
4	RTK	39.1757252250	-104.5113475472	2125.007
5	RTK	39.1804440111	-104.5131434111	2104.600
6	RTK	39.1728160917	-104.5153991833	2141.150
7	RTK	39.1747192167	-104.5185695361	2126.825
8	RTK	39.1768986056	-104.5193497139	2114.458
9	Static	39.1771775556	-104.5236606472	2098.104
10	Static	39.1785522028	-104.5264926833	2086.840
11	RTK	39.1822685778	-104.5199601528	2095.122
12	RTK	39.1775139000	-104.5164422139	2109.169
13	Static	39.1790236167	-104.5213840528	2102.151
14	RTK	39.1812713889	-104.5174793722	2099.250
15	RTK	39.1772309000	-104.5129619778	2115.481
16	RTK	39.1828786028	-104.5231034806	2097.763
17	RTK	39.1813441917	-104.5293449028	2074.902
18	RTK	39.1824924528	-104.5286269056	2084.828
19	Static	39.1832122167	-104.5281560944	2089.124
20	Static	39.1820469556	-104.5243758611	2090.066
21	Static	39.1811048583	-104.5260911667	2084.042
22	Static	39.1815434472	-104.5211844111	2089.746
23	Static	39.1790681639	-104.5226627861	2098.245
24	Static	39.1779149528	-104.5247390333	2092.533
25	RTK	39.1826855500	-104.5205383611	2098.928
26	Static	39.1804358389	-104.5203590917	2097.310
27	RTK	39.1821114167	-104.5155395306	2103.524
28	RTK	39.1818056167	-104.5143881583	2104.746
29	RTK	39.1808305278	-104.5152192722	2099.305
30	RTK	39.1788302389	-104.5188231778	2108.737
31	RTK	39.1791351750	-104.5158974778	2113.250

IMAGE DATA PROCESSING

Image data processing was completed using Agisoft Photo Scan 1.1.6 (64bit) software.
Data processing began with a visual evaluation of the images of each flight plan. Images which were not related to the project area, or images which do not have project information, such as close capture of the ground before the flight begins, were identified and deleted. The total number of collected images per flight, and the number of used for processing, are presented in the Table 6 below.

Figure 10-Table 6 – Number of images per flight

	Flight 1	Flight 2	Flight 3
Total number of collected images	773	771	848
Total number of images used for processing	763	757	64

In order to find what combinations of image data and control point collection provide for the best accuracy, the following data processing approaches were used:

- Flight 1 data was processed with all control points presenting a mixture of RTK and Static points. Project folder name: *Flight1_WGS84_composit*

- Flight 2 data was processed with all control points presenting a mixture of RTK and Static points. Project folder name: *Flight2_WGS84_composit*

- Flight 1 data was processed with Static control points. Project folder name: *Flight1_WGS84_Static*

- Flight 1 data was processed with RTK control points. Project folder name: *Flight1_WGS84_RTK*

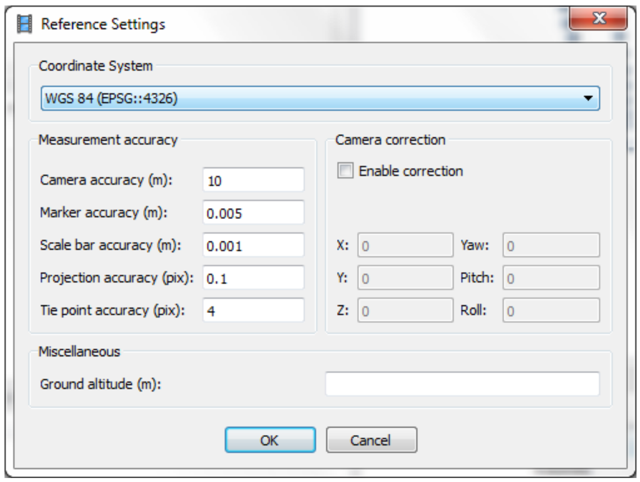
- Flight 2 data was processed with Static control points. Project folder name: *Flight2_WGS84_Static*

- Flight 2 data was processed with RTK control points: Project folder name: *Flight2_WGS84_RTK*

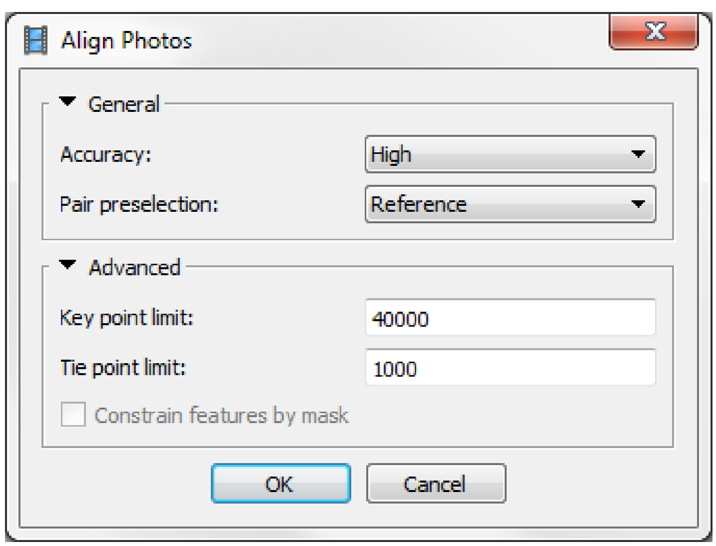
- Flight 3 data was processed by manually finding and selecting tie points and control points in about 64 images from the area of interest. Then the coordinates and Orthometric Height were entered manually and block adjustment was completed. Two subprojects were completed:
    - *Flight3_WGS84*
    - *Flight3_Local*

To keep the data processing consistent and make the final results comparable, the same steps and settings were applied during the image data processing with Photo Scan software. The order of steps and applied settings is:

1. Import images in Photo Scan
2. Visually check images and delete images which are: not related to the project area, lacking spatial information in their EXIF header, are close capture of ground before the flight began or during the landing process
3. Calculate image quality. Photo Scan has the capability to automatically find out poorly focused images and calculate the quality of the image on a scale from 0 to 1.
4. Remove images with quality less than 0.7
5. Set the project Coordinate System to WGS84

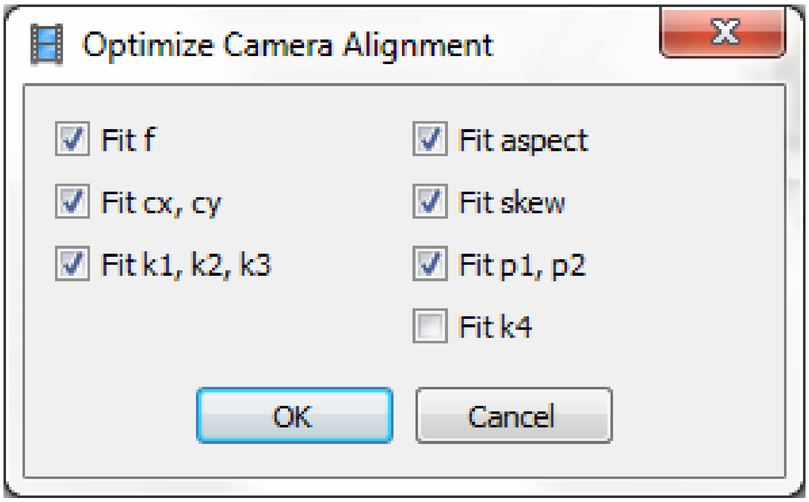


6. Align photos based on their EXIF header coordinates and set of key points automatically selected by the software

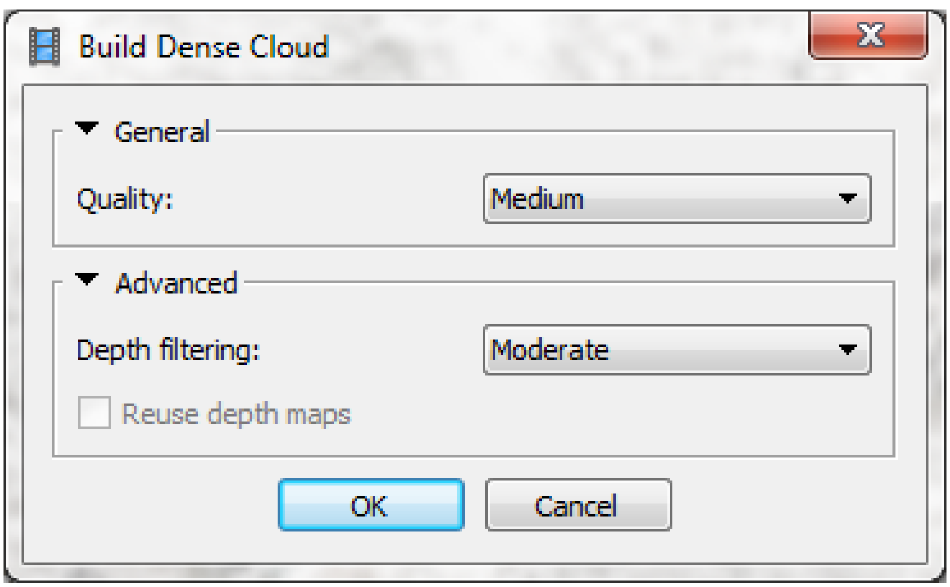


7. Identify and delete the images with no error or images at the edge of the project area which have obviously large errors after the alignment was completed

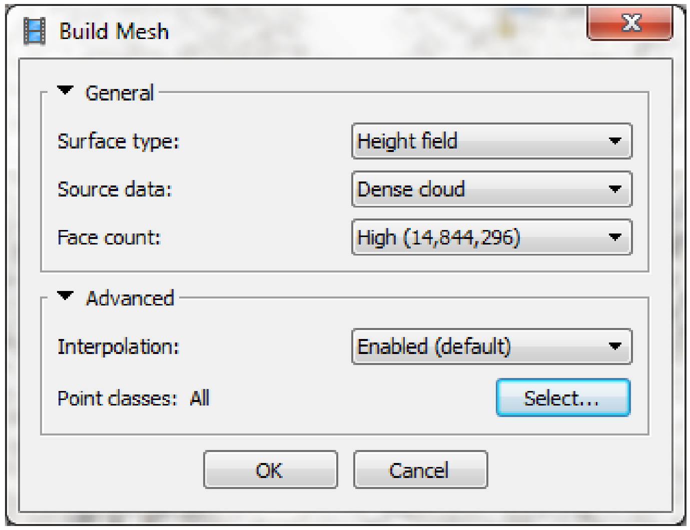
8. Import control points with their Latitude, Longitude and Ellipsoidal Height into Photo Scan
9. Automatically create markers from imported control points
10. Filter photos by marker and closely investigate the positioning of the marker on the image. Adjust the marker position if necessary to match the target position on the image or discard the image if the marker was placed on the wrong image
11. Optimize camera alignment based on markers data only



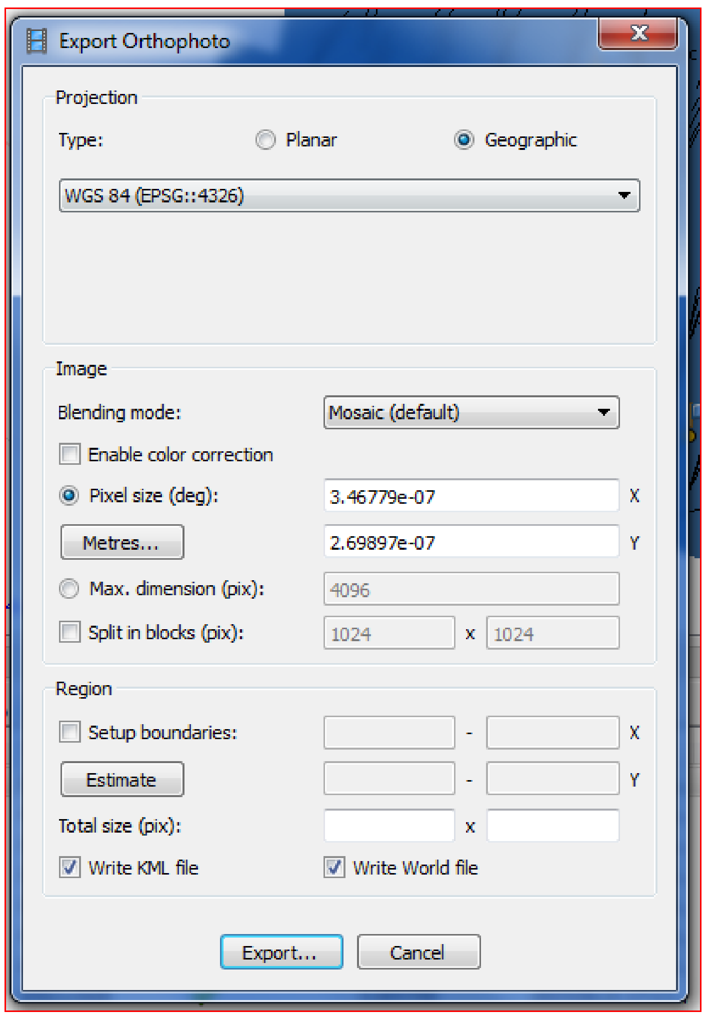
12. Build dense point cloud



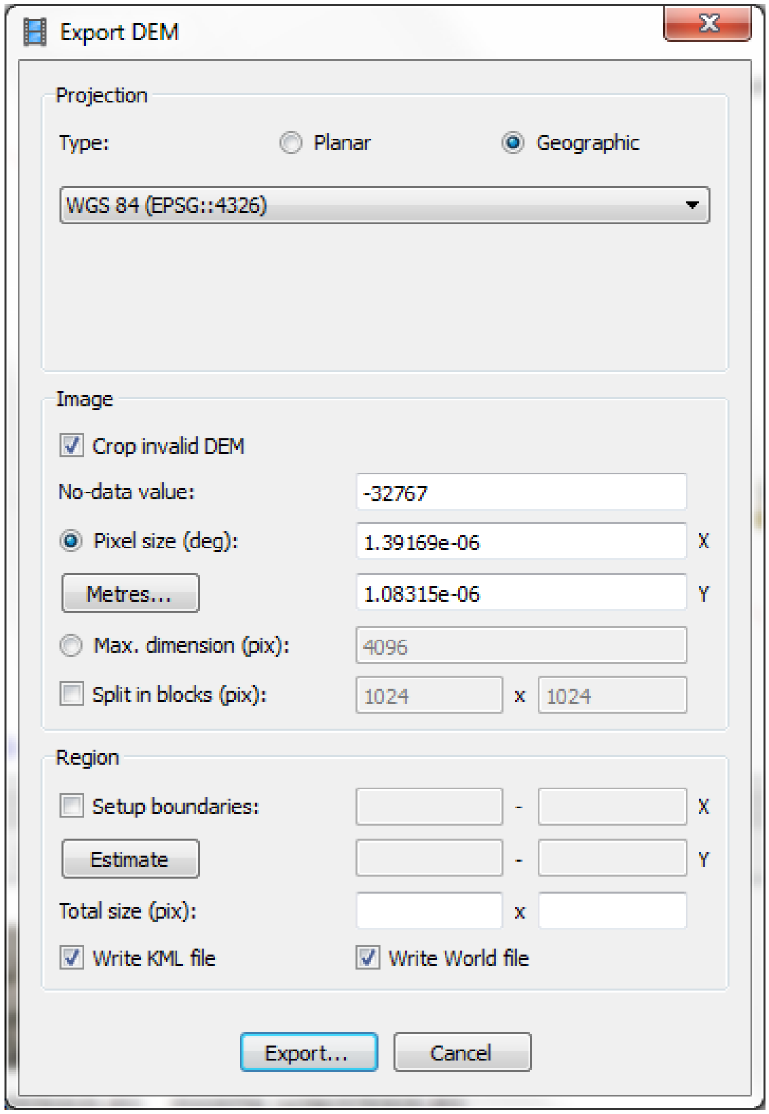
13. Build mesh



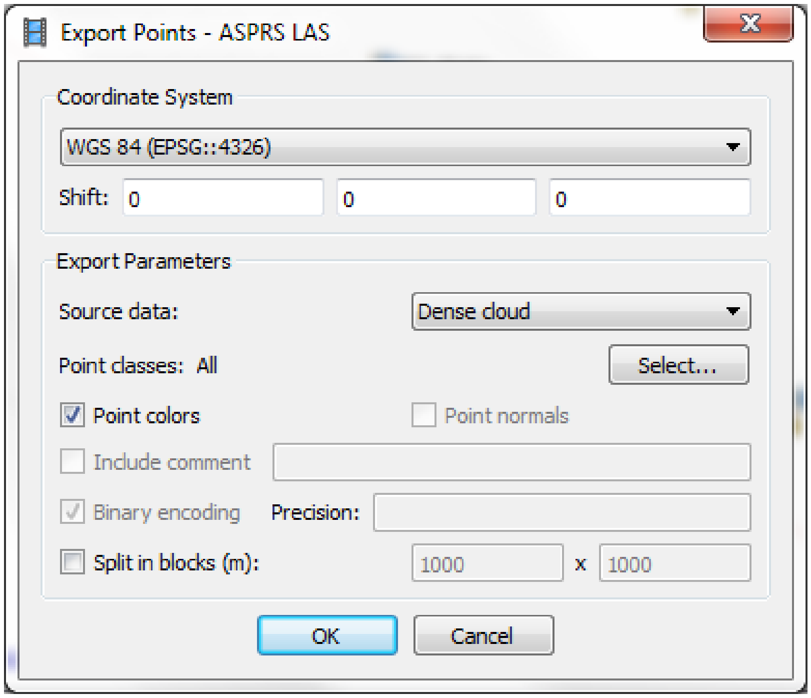
14. Export Orthophoto with associated KML and World files



15. Export DEM with associated KML and World files

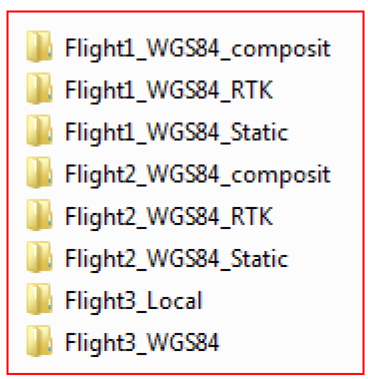


16. Export point cloud



Each process results, reports and final exports are saved in separate folders named after the flight and control point type.

Figure 11- Data folder structure



FLIGHT 3 DATA PROCESSING

Flight3 was processed differently from Flight1 and Flight2 because the images were collected with the RTK GPS unit switched off. This method of data collection does not allow for images to be matched with the flight log file and assign WGS84 coordinates and proper height, therefore the images were left "unmatched" with local coordinates instead of WGS84 coordinates in their header.

This type of data can be processed in one of two ways:

- Method 1 is based on an old school photogrammetric process that requires manual identification of tie points (photo identifiable objects) on each image and use of tie points to stitch the images together in one block or blocks. It is also important to apply proper camera calibration and orientation. After the block(s) are created, control points should be identified manually and used to complete block adjustment. This type of data processing is tedious, requires robust photogrammetric software and advanced photogrammetric skills, and is prone to errors.

Note: Method 1 one was excluded from this research because of two reasons: it requires more sophisticated professional photogrammetric software; it was intended to use only one software so the final results are comparable and do not depend on software capabilities.

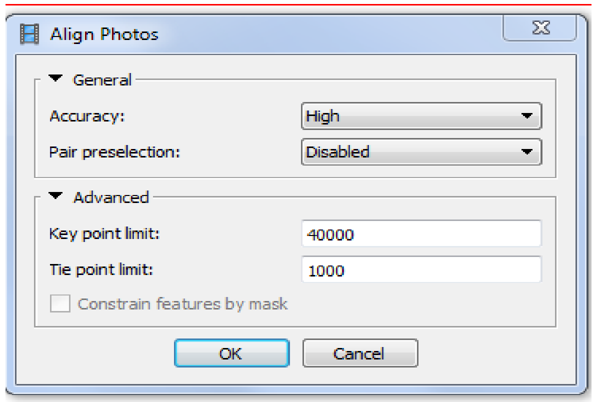
- Method 2 is to use current photogrammetric software capabilities which allow creation of a block of images based on image's local coordinates, and image number, presuming that the images are taken in a consecutive way. Then tie points are generated automatically and matched by the software. After the block is developed, control points are identified manually and block adjustment is set to run.

In both approaches Flight3_WGS 84 and Flight3_Local the final block is in WGS84 because the control points coordinates and elevations were used to transform the data into WGS84.

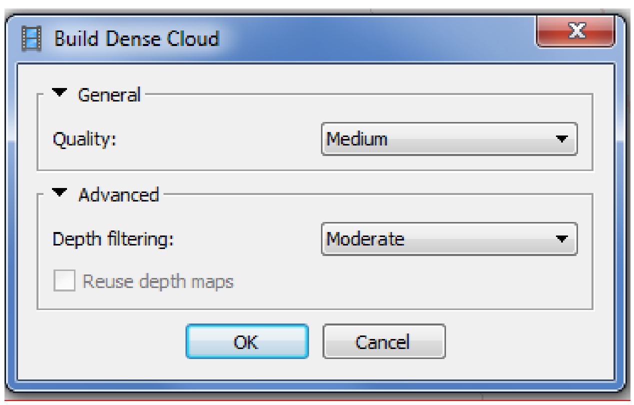
Below is an example of the Method 2 completed in WGS84 and Local coordinates. In order to compare the final results and estimate the accuracy of the Orthophoto and DEM the settings of each step were kept the same.

1. Process 1 name "Flight3_WGS84"; Process 2 name "Flight3_Local"
2. Add 64 images into Photo Scan
3. Estimate image quality and remove images with quality less than 0.7
4. Process 1 - Set the coordinate system to WGS84; Process 2 – use image's "local coordinate" system

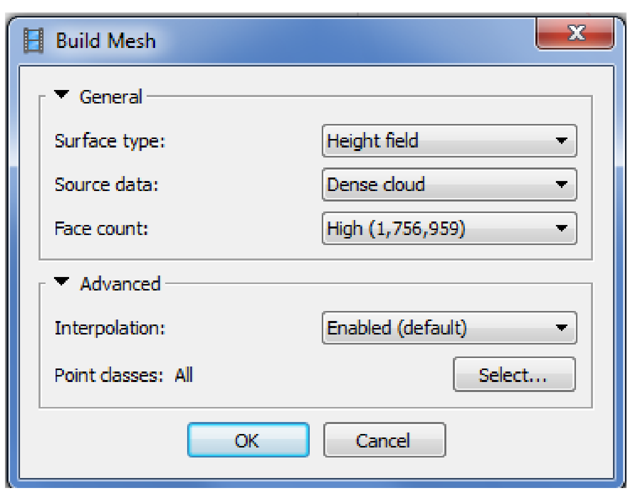
5. Align photos with disabled image pairing



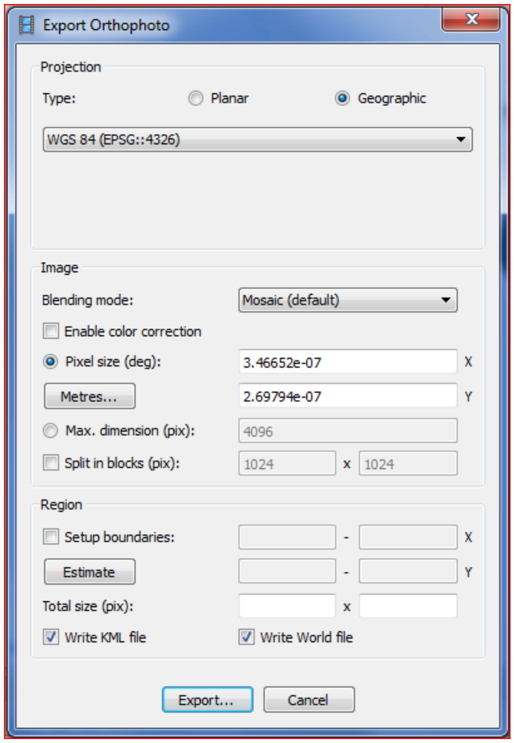
6. Import control points and place markers in each image
   6.5. For Project 2 – set coordinate system to WGS84
7. Run optimization
8. Create dense point cloud



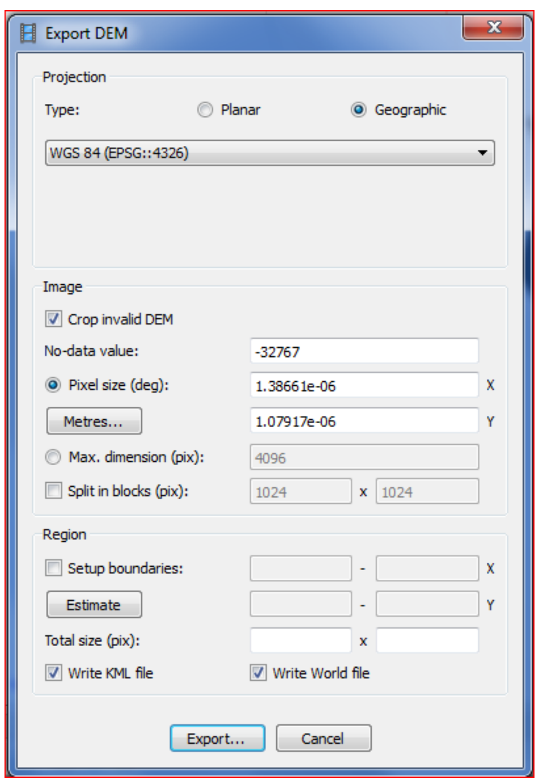
9. Build Mesh



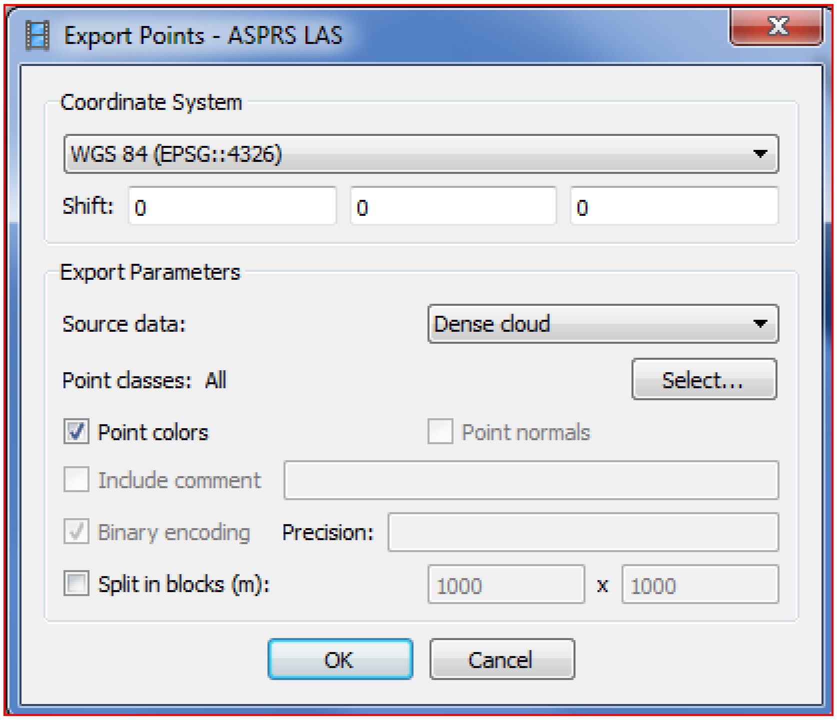
10. Export Orthophoto



11. Export DEM



12. Export Point Cloud



The results of the data processing for Flight3 are saved in Flight3_WGS84 and Flight3_Local folders. The name Flight3_Local indicate that the initial image alignment was completed in the so called "local coordinate system", but the final results such as DEM, Point Cloud, and Orthophoto are in WGS84 because the block adjustment was based on control point's data. The same control points (11, 22, and 26) were used in both approaches.
The determination of the errors was done following the steps already completed in Flight1 and Flight2.

1. Orthophoto and DEM were imported into ArcMap
2. Points feature classes CP_Fligh3_WGS84 and CP_Fight3_Local were created
3. Control points coordinates and ellipsoidal heights were extracted from the Orthophoto and DEM data
4. ECEF coordinates were calculated and then compared to the original ECEF coordinates of the control to calculate the difference DX, DY, DZ and DS as well as RMSE and accuracy at 95%

RESULTS AND ANALYSIS OF ACCURACY (Flight1 and Flight2)

The results of data processing are found in the reports provided by Photo Scan. Two different reports were created for each Flight 1 and Flight 2 projects. The first report was exported after image alignment based on EXIF data. The summary of these reports is presented in *RESULTS AND STATISCS.XLSX* file, tab “Align photos reports”.

Figure 12-Table 7- Summary of aligned photos reports

PARAMETERS	Flight1_WGS84_composit	Flight1_WGS84_RTK	Flight1_WGS84_Static	Flight2_WGS84_composit	Flight2_WGS84_RTK	Flight2_WGS84_Static
Number of images:	763	763	763	733	733	733
Flying altitude:	123.895	124.36	124.36	122.991	122.991	122.96
Ground resolution:	0.0323793	0.032501	0.032501	0.0321642	0.0321642	0.0297836
Coverage area:	0.160548	0.161725	0.161725	0.151254	0.151254	0.151408
Camera stations:	763	763	763	733	733	733
Tie-points:	82366	86733	86733	87449	87449	87449
Projections:	643974	654420	654420	646417	646417	646417
Error: (pixel)	1.0162	1.01202	1.01202	0.9754	0.9754	0.833148
Camera Settings						
Resolution	4592x3448	4592x3448	4592x3448	4592x3448	4592x3448	4592x3448
Focal length	14	14	14	14	14	14
Pixel size	3.76729 x 3.76729um	3.76729 x 3.76729um	3.76729 x 3.76729um	3.76729 x 3.76729um	3.76729 x 3.76729um	3.76729 x 3.76729um
Image residuals						
Fx	382635	3826.35	3826.35	3823.85	3823.85	3825.88
Fy	3826.35	3826.35	3826.35	3823.85	3823.85	3825.94
Cx	2241.9	2271.9	2271.9	2273.56	2273.56	2255.59
Cy	1702.17	1702.17	1702.17	1700.71	1700.71	1702
Skew	0	0	0	0	0	0
K1	-0.0486736	-0.0486736	-0.0486736	-0.04811284	-0.04811284	-0.0478685
K2	0.0374343	0.0374343	0.0374343	0.0375808	0.0375808	0.037586
K3	-0.0245541	-0.0246541	-0.0246541	-0.0246075	-0.0246075	-0.0223921
K4	0	0	0	0	0	0
P1	0	0	0	0	0	-0.00000008
P2	0	0	0	0	0	-0.00178068
Average camera location error (m)						
X error (m)	1.463022	0.343772	0.343772	0.161862	0.391462	0.278052
Y error (m)	1.468	0.334555	0.334555	0.12575	0.474713	0.48458
Z error (m)	6.091328	1.249031	1.249031	0.117379	0.86537	1.918551
Total error (m)	2.341476	1.337978	1.337978	0.2362	1.061819	1.998168
DEM range (m)						
Min	1916.37	1916.37	1916.37	1934.25	1934.25	1935.96
Max	2188.47	2188.47	2188.47	2180.22	2180.22	2182.28

The summary presents that flights were taken at an average of 123m above ground with ground resolution of 3cm. Due to the usage of a pre-calibrated camera, the image residuals are almost the same for both flights. The average camera location was calculated by Photo Scan based on coordinates of EXIF header.

The second report was exported after the camera optimization was completed based on control point markers. Control points and check points errors summary is provided in *RESULTS AND STATISCS.XLSX* file, tab *“Camera optimization reports”.* Each report has a table showing the errors for control points after the optimization process was completed. An example of Flight1_WGS84_composit, Table 8, and Flight1_WGS84_RTK, Table 9, are presented below.

Figure 13-Table 8 - Flight1_WGS84_composit report

CP	X error(m)	Y error (m)	Z error (m)	Error (m)	Error (pix)
Flight1_WGS84_composit					
5_RTK	0.012975	0.007305	0.001762	0.014994	0.07244
8_RTK	0.002394	-0.0016	0.00366	0.004657	0.046757
9_Static	-0.000585	-0.002011	-0.000448	0.002141	0.059419
11_RTK	-0.011607	0.000393	0.01083	0.01588	0.074589
12_RTK	-0.003185	0.007122	-0.000214	0.007805	0.092223
13_Static	0.025043	0.003666	0.00724	0.026325	0.694825
14_RTK	-0.01166	-0.015944	0.004703	0.020305	0.072522
22_Static	-0.002387	-0.004162	0.001999	0.005197	0.077816
23_Static	-0.012312	0.00607	-0.007319	0.015557	0.082828
25_RTK	0.009577	0.003845	-0.006966	0.012451	0.095871
26_Static	-0.0171	-0.004586	-0.00662	0.018901	0.056206
27_RTK	-0.011463	-0.006143	-0.001965	0.013153	0.092577
28_RTK	-0.000431	0.001225	-0.004401	0.004589	0.091307
29_RTK	0.013837	-0.041116	0.006388	0.04385	0.098171
30_RTK	-0.024011	0.017149	-0.005431	0.030001	0.084054
31_RTK	0.03025	0.028779	-0.005941	0.042173	0.140415
Total	**0.01466**	**0.014406**	**0.005519**	**0.021281**	**0.203096**

Figure 14-Table 9 - Flight1_WGS84_RTK report

CP	X error(m)	Y error (m)	Z error (m)	Error (m)	Error (pix)
Flight1_WGS84_RTK					
Control points error					
5_RTK	0.013414	0.006935	0.001665	0.015192	0.072967
8_RTK	0.004646	-0.000467	0.003628	0.005913	0.050867
11_RTK	-0.012636	-0.00058	0.009919	0.016075	0.07372
12_RTK	-0.002079	0.006885	0.000544	0.007213	0.091786
14_RTK	-0.013517	-0.014436	0.005676	0.020575	0.074506
25_RTK	0.006368	0.002579	-0.008699	0.011085	0.095378
27_RTK	-0.011862	-0.006315	-0.000643	0.013454	0.092499
28_RTK	-0.000497	0.000313	-0.004621	0.004658	0.09117
29_RTK	0.013902	-0.040723	0.005685	0.043404	0.098383
30_RTK	-0.028114	0.017483	-0.007796	0.034012	0.084757
31_RTK	0.030836	0.028823	-0.00594	0.042625	0.140241
Total	**0.015563**	**0.016911**	**0.005821**	**0.023708**	**0.0947**
Check points error					
9_Static	-0.141151	-0.289087	-1.051852	1.099949	0.059532
13_Static	-0.002247	-0.007639	-0.29403	0.294138	0.690747
22_Static	-0.00752	-0.000605	-0.199894	0.200037	0.07868
23_Static	-0.082533	-0.018848	-0.768184	0.772835	0.084575
26_Static	-0.036324	-0.002748	-0.205221	0.208429	0.05585
Total	**0.074989**	**0.129609**	**0.610741**	**0.62883**	**0.340208**

Flight1 and Flight2 composite reports do not have errors for “Check points” because all control points were used for optimization. The RTK and Static reports for both Flight1 and Flight2 provide two different set of errors. One set is for control points used to optimize the images and the second set is for check points, which actually are control points not used for optimization, but are present in the project area. Table 10, representing errors per flight and processing type was generated.

Figure 15-Table 10 - Summary of errors

CONTROL POINTS ERROS PER FLIGHT AND CP TYPE					
FLIGHT	X error(m)	Y error (m)	Z error (m)	Error (m)	Error (pix)
Flight1_WGS84_composit	0.0147	0.0144	0.0055	0.0213	0.2031
Flight1_WGS84_RTK	0.0156	0.0169	0.0058	0.0237	0.0947
Flight1_WGS84_Static	0.0158	0.0079	0.0059	0.0187	0.3418
Flight2_WGS84_composit	0.0099	0.0071	0.0061	0.0137	0.0919
Flight2_WGS84_RTK	0.0116	0.0082	0.0063	0.0155	0.0943
Flight2_WGS84_Static	0.0010	0.0013	0.0018	0.0024	0.0869
CHECK POINTS ERROS PER FLIGHT AND CP TYPE					
FLIGHT	X error(m)	Y error (m)	Z error (m)	Error (m)	Error (pix)
Flight1_WGS84_RTK	0.0750	0.1296	0.6107	0.6288	0.3402
Flight1_WGS84_Static	0.1312	0.0789	1.1301	1.1404	0.0936
Flight2_WGS84_RTK	0.0144	0.0438	0.0524	0.0697	0.0856
Flight2_WGS84_Static	0.1440	0.1147	0.3721	0.4152	0.0947

After the data was processed by Photo Scan and reports were exported and summarized, then the list with original coordinates in WGS84 of the control points was used to develop *“ControlPoints_WGS84”* ArcGIS feature class. The *“ControlPoints_WGS84”* feature class was added into ArcGIS Map and orthophoto of each project approach was overlaid. A new point feature class was created for each of the processed categories aka “CP_Flight1_WGS84_RTK”. The coordinates of the control points were extracted from each orthophoto and were saved in the relevant point feature class. Then each DEM file was overlaid and ellipsoidal heights were calculated for the same control point. Having the geodetic coordinates and Ellipsoidal Heights the next step was to calculate ECEF coordinates for control points. The ECEF coordinates were used to calculate the 3D vector difference between the original control point’s position and the position of control points calculated from orthophoto and DEM data. Summary of the 3D vector calculation is presented in Table 10 where DX, DY, DZ and DS (3D vector) are averaged differences in participating control points per each processing approach.

Figure 16-Table 11 - Average error of control points

SUMMARY OF AVERAGE ERRORS IN ECEF COORDINATES				
Process type	**Dx**	**Dy**	**Dz**	**Ds**
CP_Flight1_WGS84_composit	-0.0012	0.0163	-0.0032	0.0293
CP_Flight1_WGS84_RTK	-0.0114	-0.0921	0.1076	0.1859
CP_Flight1_WGS84_Static	-0.1811	-0.3757	0.3901	0.6078
CP_Flight2_WGS84_composit	0.0003	0.0100	-0.0082	0.0261
CP_Flight2_WGS84_RTK	-0.0073	-0.0059	0.0043	0.0331
CP_Flight2_WGS84_Static	-0.0044	0.1804	-0.1956	0.2873
CP_Flight3_WGS84	-88.9110	-174.6867	-221.4093	445.1742
CP_Fligh3_Local	-88.9121	-174.6922	-221.4178	445.1785

The averaged differences from Table 11 were used to compute RMSE and Accuracy at 95% confidence which data is presented in Table 12.

Figure 17-Table 12 - Summary of RMSE and Accuracy at 95% for control points in each processing type

SUMMARY OF RMSE AND 95% ACCURACY FROM ECEF COORDINATES					
Process type		**Dx**	**Dy**	**Dz**	**Ds**
CP_Flight1_WGS84_composit	RMSE	0.0047	0.0650	0.0130	0.1172
	Accuracy at 95%	0.0092	0.1274	0.0254	0.2297
CP_Flight1_WGS84_RTK	RMSE	0.0456	0.3685	0.4303	0.7435
	Accuracy at 95%	0.0893	0.7222	0.8433	1.4573
CP_Flight1_WGS84_Static	RMSE	0.7242	1.5030	1.5605	2.4311
	Accuracy at 95%	1.4195	2.9458	3.0586	4.7649
CP_Flight2_WGS84_composit	RMSE	0.0014	0.0412	0.0337	0.1077
	Accuracy at 95%	0.0027	0.0807	0.0661	0.2111
CP_Flight2_WGS84_composit	RMSE	0.0136	0.0098	0.0184	0.1640
	Accuracy at 95%	0.0267	0.0193	0.0361	0.3213
CP_Flight2_WGS84_Static	RMSE	0.0169	0.6986	0.7576	1.1128
	Accuracy at 95%	0.0332	1.3692	1.4849	2.1811
CP_Flight3_WGS84	RMSE	68.87019028	135.3117076	171.5029141	344.8304234
	Accuracy at 95%	134.9855729	265.2109469	336.1457116	675.8676298
CP_Fligh3_Local	RMSE	68.87098295	135.3160092	171.5094956	344.8338067
	Accuracy at 95%	134.9871266	265.219378	336.1586113	675.8742612

CONCLUSIONS

The results of this research inevitably prove that UAV image data collection can produce final orthophoto, DEM, and Point Cloud with accuracy in the centimeter range - as is shown in Table 10 and Table 11.

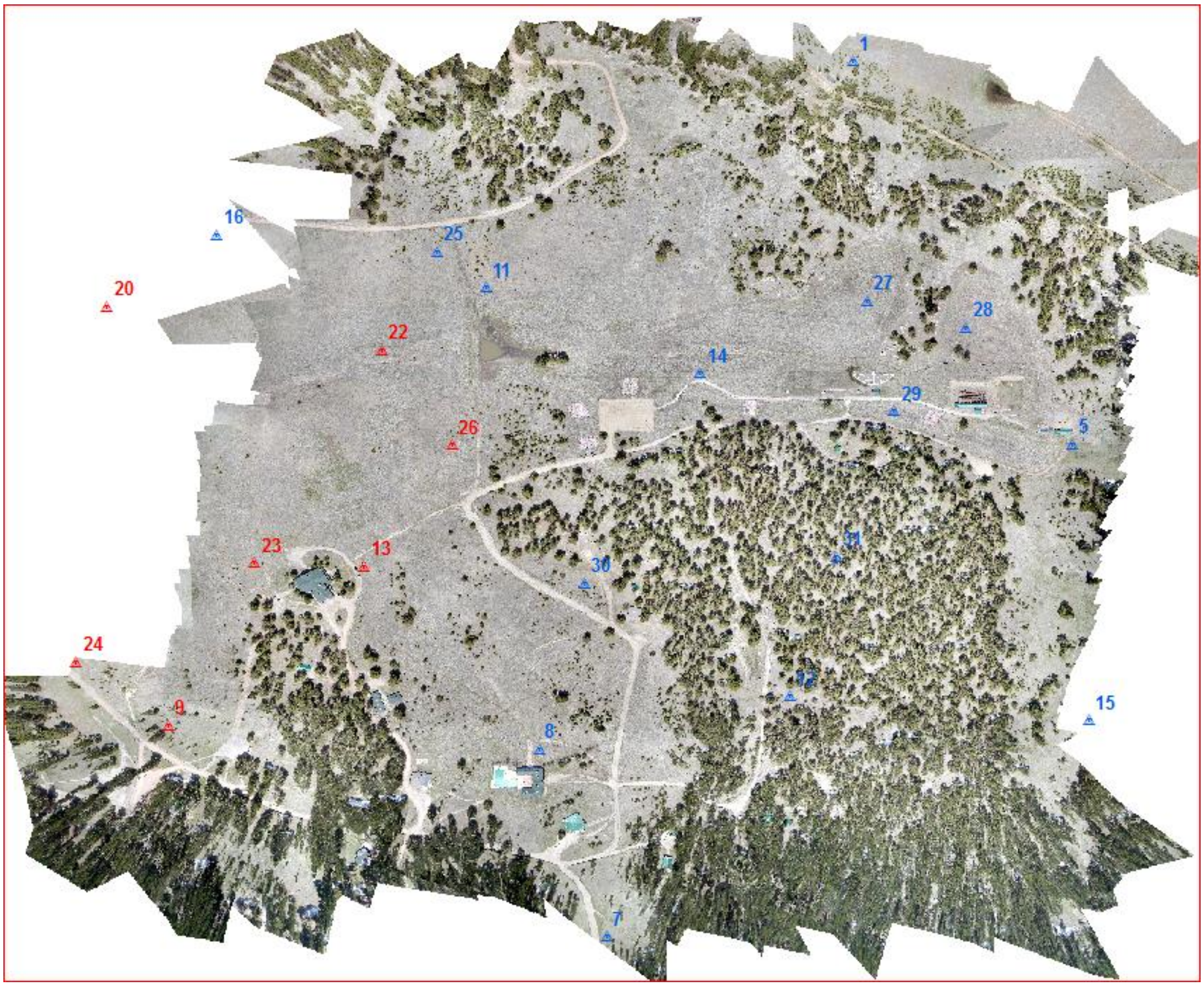
It is also clear that the final product accuracy is not really dependent on the method of the control point's data collection, Static vs. RTK, but rather on even distribution of control points across the project area, properly calibrated camera, following standard surveying practices to establish and collect control and check points and standard photogrammetric procedure for data processing. This can be proven by comparing the results of data accuracy along processing path. In the Table 13 below can be seen that the worst results are shown in three places: Flight3, Flight1_WGS84_Static and Flight2_WGS84_Static.

Figure 18-Table 13 - Summary of errors, RMSE and accuracy at 95% confidence

CP_Flight1_WGS84_composit	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS			CHECK POINTS		
Align photos report	1.4630	1.4680	6.0913	2.3415	TOTAL	RTK	STATIC	TOTAL	RTK	STATIC
Optimization report	0.0147	0.0144	0.0055	0.0213	16	11	5	NA	NA	NA
ECEF coordinate error	-0.0012	0.0163	-0.0032	0.0293						
RMSE	0.0047	0.0650	0.0130	0.1172						
Accuracy at 95%	0.0092	0.1274	0.0254	0.2297						
CP_Flight1_WGS84_RTK	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS			CHECK POINTS		
Align photos report	0.3438	0.3346	1.2490	1.3380	TOTAL	RTK	STATIC	TOTAL	RTK	STATIC
Optimization report	0.0156	0.0169	0.0058	0.0237	11	11	NA	5	NA	5
ECEF coordinate error	-0.0114	-0.0921	0.1076	0.1859						
RMSE	0.0456	0.3685	0.4303	0.7435						
Accuracy at 95%	0.0893	0.7222	0.8433	1.4573						
CP_Flight1_WGS84_Static	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS			CHECK POINTS		
Align photos report	0.3438	0.3346	1.2490	1.3380	TOTAL	RTK	STATIC	TOTAL	RTK	STATIC
Optimization report	0.0158	0.0079	0.0059	0.0187	5	NA	5	11	11	NA
ECEF coordinate error	-0.1811	-0.3757	0.3901	0.6078						
RMSE	0.7242	1.5030	1.5605	2.4311						
Accuracy at 95%	1.4195	2.9458	3.0586	4.7649						
CP_Flight2_WGS84_composit	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS			CHECK POINTS		
Align photos report	0.1619	0.1258	0.1174	0.2362	TOTAL	RTK	STATIC	TOTAL	RTK	STATIC
Optimization report	0.0099	0.0071	0.0061	0.0137	17	12	5	NA	NA	NA
ECEF coordinate error	0.0003	0.0100	-0.0082	0.0261						
RMSE	0.0014	0.0412	0.0337	0.1077						
Accuracy at 95%	0.0027	0.0807	0.0661	0.2111						
CP_Flight2_WGS84_RTK	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS			CHECK POINTS		
Align photos report	0.3915	0.4747	0.8654	1.0618	TOTAL	RTK	STATIC	TOTAL	RTK	STATIC
Optimization report	0.0116	0.0082	0.0063	0.0155	12	12	NA	5	NA	5
ECEF coordinate error	-0.0073	-0.0059	0.0043	0.0331						
RMSE	0.0136	0.0098	0.0184	0.1640						
Accuracy at 95%	0.0267	0.0193	0.0361	0.3213						
CP_Flight2_WGS84_Static	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS			CHECK POINTS		
Align photos report	0.2781	0.4846	1.9186	1.9982	TOTAL	RTK	STATIC	TOTAL	RTK	STATIC
Optimization report	0.0010	0.0013	0.0018	0.0024	4	NA	4	11	11	NA
ECEF coordinate error	-0.0044	0.1804	-0.1956	0.2873						
RMSE	0.0169	0.6986	0.7576	1.1128						
Accuracy at 95%	0.0332	1.3692	1.4849	2.1811						
CP_Flight3_WGS84	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS					
Align photos report			NA		3					
Optimization report										
ECEF coordinate error	-88.9110	-174.6867	-221.4093	445.1742						
RMSE	68.8702	135.3117	171.5029	344.8304						
Accuracy at 95%	134.9856	265.2109	336.1457	675.8676						
CP_Fligh3_Local	X error (m)	Y error (m)	Z error (m)	Total error (m)	CONTROL POINTS					
Align photos report			NA		3					
Optimization report										
ECEF coordinate error	-88.9121	-174.6922	-221.4178	445.1785						
RMSE	68.87098	135.31601	171.50950	344.83381						
Accuracy at 95%	134.98713	265.21938	336.15861	675.87426						

The explanation for Flight1_WGS84_Static and Fligh2_WGS84_Static is simple: Static control points are clustered on one side of the project area and RTK points are covering another portion of the project area. Another factor is also the number of points used to optimize the image cluster. It is clearly seen in the image below that static points were only 5, versus RTK points which are 12. Thus, the small number of points and their uneven distribution cannot provide solid information for image optimization of the entire project area if only one set of points, RTK or Static control, is used for fine block adjustment.

Figure 19 – RTK (blue) and Static (red) control points



This reflects directly in the quality of the final generated product as DEM and Orthophoto since they will inherit these inaccuracy. The errors could be significant, as it is in the Flight1_WGS84_Static process case. On the other hand, when all control points were used as was the case in Flight1_WGS84_composit and Flight2_WGS84_composit, the errors are very small and the final product is highly accurate.

FLIGHT3 RESULTS, ANALYSES AND CONCLUSIONS

The analysis and results of Flight 3 are discussed distinct and separately because of the fact that the data was collected in the hobbyist manner without any GPS units attached to the camera and unknown camera calibration parameters. This data processing was performed only to show that "wild" data collection without following standard photogrammetric practice and understanding the principals of photogrammetry can be very dangerous. Apparently the data can be processed and final product like Orthophoto and DEM can be generated. The accuracy level could be very high as it is shown in the *Flight3_Local_optimization report.pdf* and *Flight3_WGS84_optimization report.pdf* documents.

Figure 20 - Error report from Flight3_Local

Label	X error (m)	Y error (m)	Z error (m)	Error (m)	Projections	Error (pix)
11_RTK	0.002142	-0.004495	0.001990	0.005362	5	0.113720
22_Static	-0.005567	0.002221	-0.000449	0.006011	13	0.103378
26_Static	0.003626	0.001432	0.000226	0.003905	9	0.096648
Total	**0.004031**	**0.003010**	**0.001185**	**0.005168**	**27**	**0.103219**

Table. 2. Control points.

Figure 21 - Error report from Flight3_WGS84

Label	X error (m)	Y error (m)	Z error (m)	Error (m)	Projections	Error (pix)
11_RTK	0.002250	-0.004462	0.001993	0.005380	5	0.116683
22_Static	-0.005655	0.002090	-0.000449	0.006046	13	0.115980
26_Static	0.003610	0.001533	0.000224	0.003928	9	0.075264
Total	**0.004086**	**0.002979**	**0.001187**	**0.005194**	**27**	**0.104337**

Table. 2. Control points.

The errors are so small that the acceptance of this relative accuracy for true accuracy can lead to a dangerous path of use of spatially incorrect data. The data in Figure 22 and Figure 23 presents the actual errors, RMSE, and accuracy.

Figure 22 - ECEF errors, RMSE and 95% confidence level for Flight3_Local

	ECEF COORDINATES DIFFERENCE			
	DX	DY	DZ	DS
	-47.127	-392.441	-450.088	599.008
	-285.639	-249.117	-370.574	530.069
	66.030	117.481	156.408	206.459
AVERAGE	-88.9121	-174.692	-221.418	445.1785
RMSE	68.87098	135.316	171.5095	344.8338
Accuracy at 95%	134.9871	265.2194	336.1586	675.8743

Figure 23 - ECEF errors, RMSE and 95% confidence level for Flight3_WGS84

	ECEF COORDINATES DIFFERENCE			
	DX	DY	DZ	DS
	-47.122	-392.445	-450.058	598.988
	-285.644	-249.113	-370.573	530.070
	66.033	117.498	156.403	206.465
AVERAGE	-88.911	-174.687	-221.409	445.174
RMSE	68.870	135.312	171.503	344.830
Accuracy at 95	134.986	265.211	336.146	675.868

The errors are in meters, with maximum error being in DZ (ellipsoidal height).

Where did such big errors come from if this block of 64 images was adjusted by control points?

The answer is in the process which most of the UAV users employ to generate quick and apparently inaccurate, but good looking data. Current software applications rely on automatic ways of point recognition and then match these points to combine images together and generate point cloud. While there is nothing wrong with this technique, one of the main factors which is not taken into account is the camera calibration and camera orientation. The determination of exact interior orientation parameters is playing a high role in precise object reconstruction. Miscalculation of the exact camera position directly affects the accuracy of the point cloud. Another important factor is the number and positional accuracy of the control points used for exterior orientation. In Flight 3 case the positional accuracy of the control point is in centimeter level. However, the errors are so big because Flight 3 was processed without a photo log to provide detailed information about interior orientation, no GPS coordinates on EXIF header, and only three control points for exterior orientation.

RECOMMENDATIONS

This research project certainly proves that despite the UAV capability to fly low and collect images with resolution of 2-3cm, it is still very important to follow the standard photogrammetric practice for data collection and processing. Based on the lessons learned from this project it is suggested that the following recommendations be taken in account:

- Prepare detailed project documentation based on standard photogrammetric practice which includes, but is not limited to flight planning, control and check points site selection and marking
- It is strongly advised that the locations and marking of the control and check points is carefully planned and evenly distributed across the project area
- GPS data collection of the control points to follow standard surveying practices and be properly post processed
- GPS data collection and processing should be completed before image data collection is executed
- The UAV GPS and the GPS used to survey control points have the right Datum and Geoid
- Control points and image data should be in the same coordinate system
- Use calibrated high resolution camera to avoid problems with image quality and minimize lens distortions
- The RTK enabled GPS onboard UAV should not be turned off
- Post processing of the images to attach the coordinates from UAV image log file into their EXIF header is required
- Image optimization (fine block adjustment) should be based on accurate control points
- It is advisable to employ more robust photogrammetric software which allows higher project control by manually digitizing tie points in the case of missing coordinates in images EXIF header